



US009423303B2

(12) **United States Patent**
Samarao et al.

(10) **Patent No.:** **US 9,423,303 B2**

(45) **Date of Patent:** **Aug. 23, 2016**

(54) **MEMS INFRARED SENSOR INCLUDING A PLASMONIC LENS**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 231 days.

(21) Appl. No.: **14/136,808**

(22) Filed: **Dec. 20, 2013**

(65) **Prior Publication Data**

US 2014/0294043 A1 Oct. 2, 2014

Related U.S. Application Data

(63) Continuation-in-part of application No. 14/091,550, filed on Nov. 27, 2013.

(60) Provisional application No. 61/745,571, filed on Dec. 22, 2012, provisional application No. 61/731,995, filed on Nov. 30, 2012.

(51) **Int. Cl.**

G01J 5/02 (2006.01)

G01J 5/10 (2006.01)

G01J 5/20 (2006.01)

G01J 5/04 (2006.01)

G01J 5/08 (2006.01)

(52) **U.S. Cl.**

CPC **G01J 5/024** (2013.01); **G01J 5/045** (2013.01); **G01J 5/0815** (2013.01); **G01J 5/0837** (2013.01); **G01J 5/0856** (2013.01); **G01J 5/10** (2013.01); **G01J 5/20** (2013.01)

(58) **Field of Classification Search**

CPC G01J 5/024

See application file for complete search history.

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Primary Examiner — David Porta

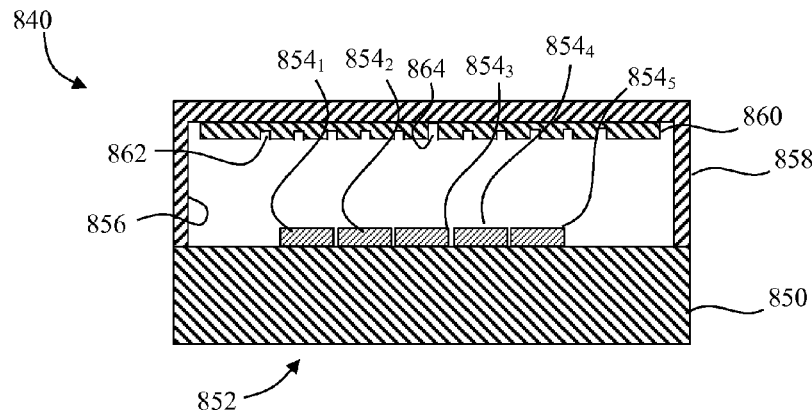
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(57) **ABSTRACT**

A portable thermal imaging system includes a portable housing configured to be carried by a user, a bolometer sensor assembly supported by the housing and including an array of thermal sensor elements and at least one plasmonic lens, a memory including program instructions, and a processor operably connected to the memory and to the sensor, and configured to execute the program instructions to obtain signals from each of a selected set of thermal sensor elements of the array of thermal sensor elements, assign each of the obtained signals with a respective color data associated with a temperature of a sensed object, and render the color data.

16 Claims, 14 Drawing Sheets



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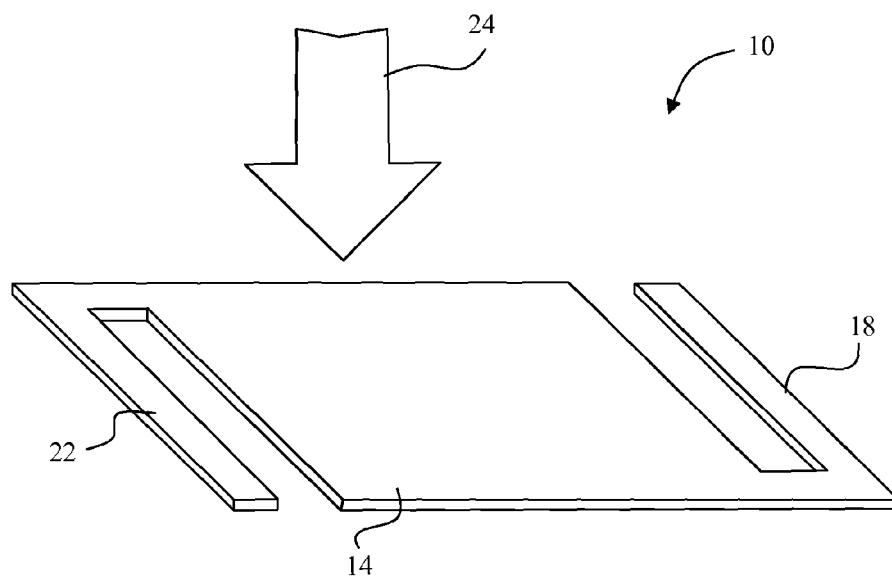


FIG. 1
(PRIOR ART)

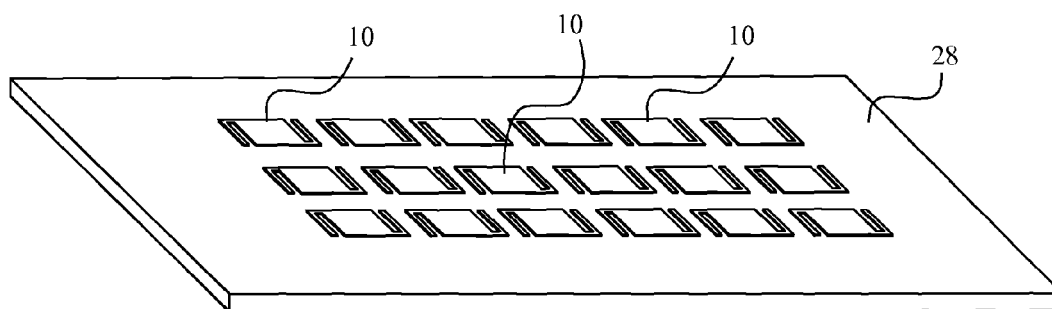


FIG. 2
(PRIOR ART)

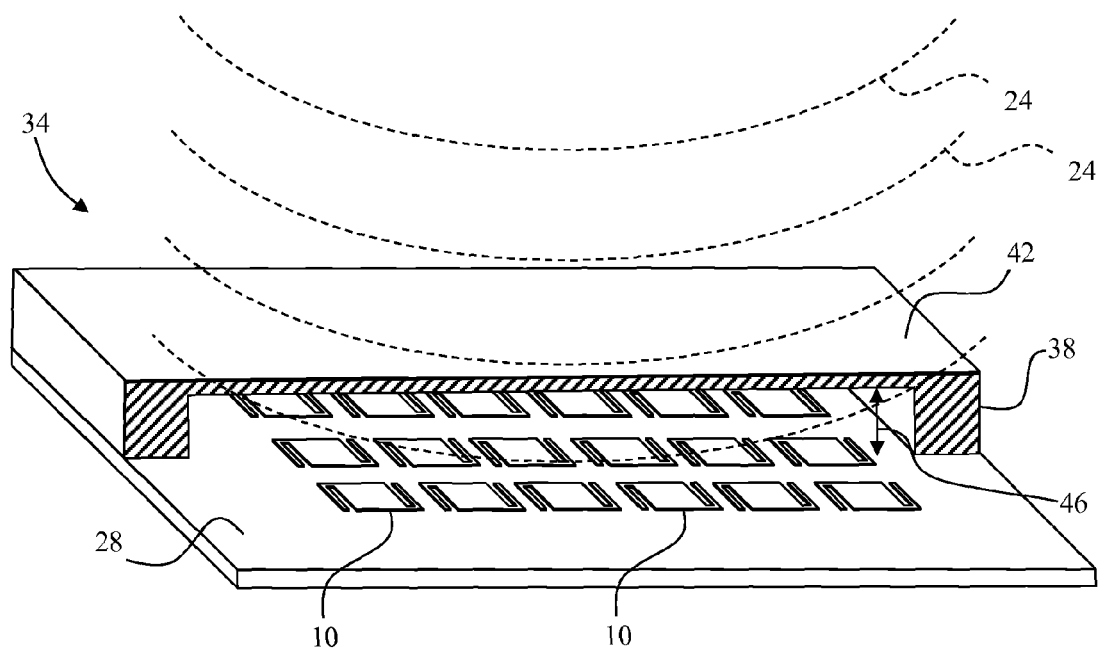


FIG. 3
(PRIOR ART)

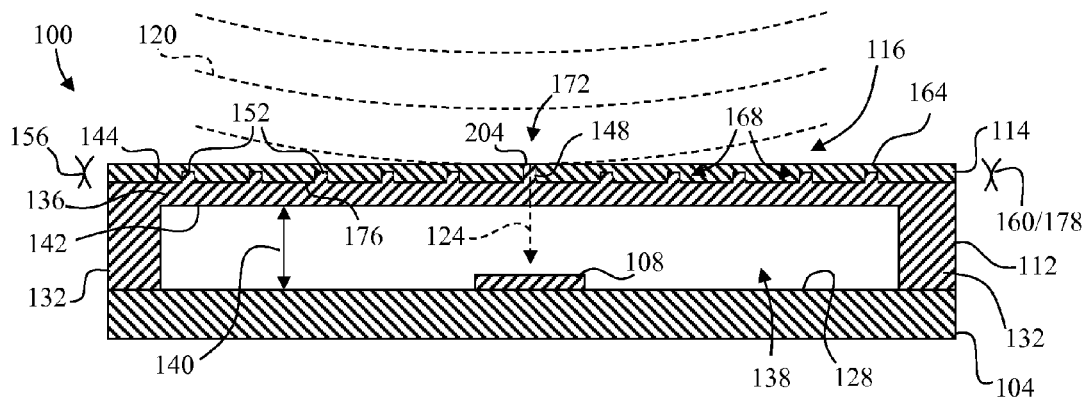


FIG. 4

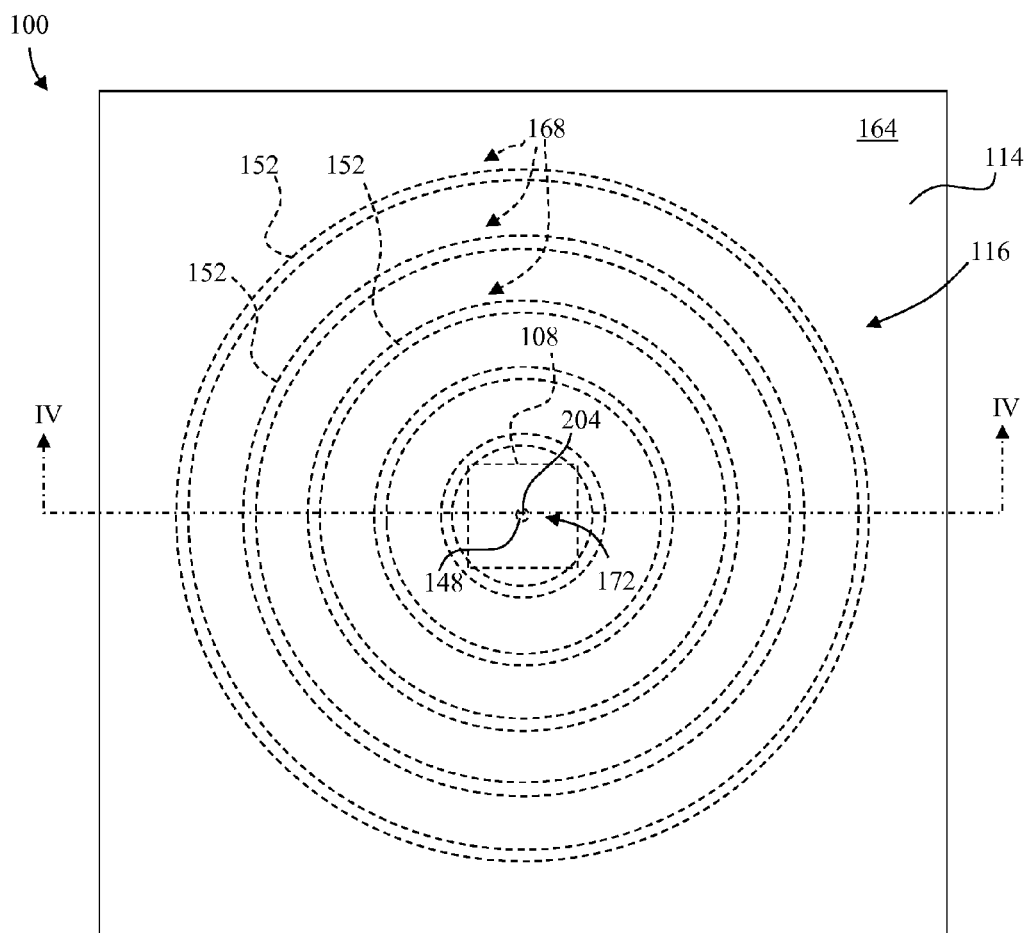


FIG. 5

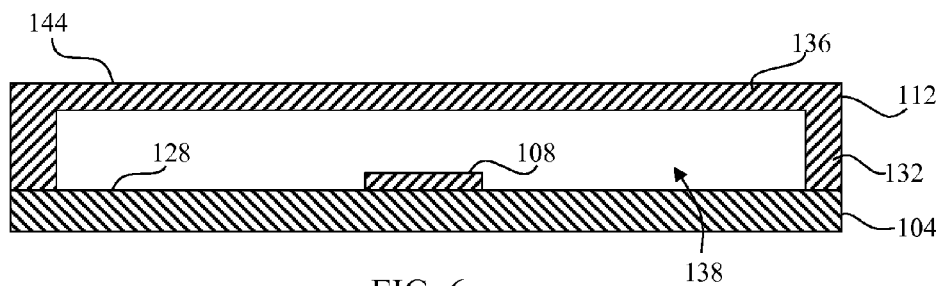


FIG. 6

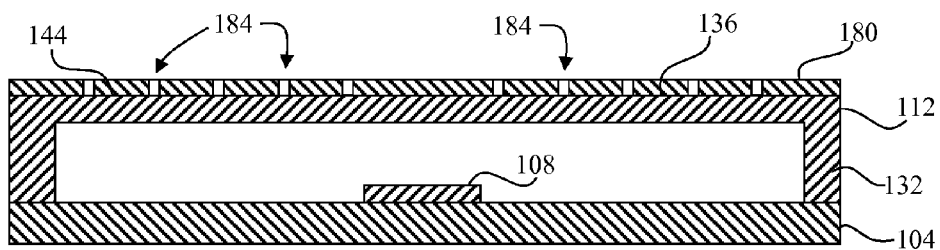


FIG. 7

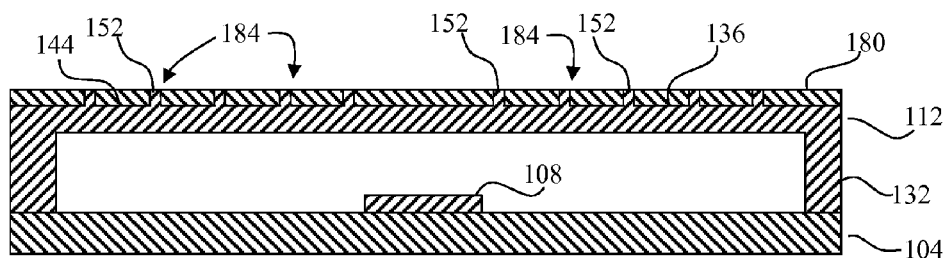


FIG. 8

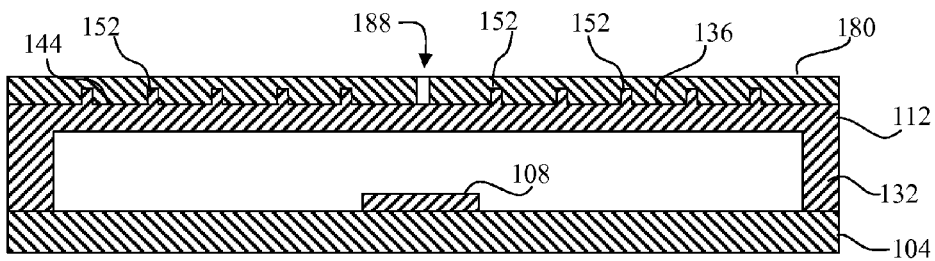


FIG. 9

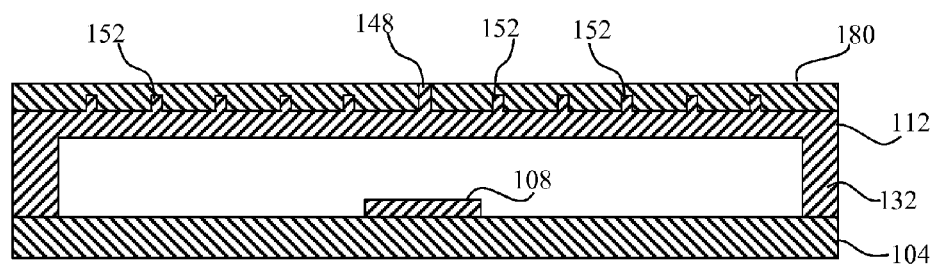


FIG. 10

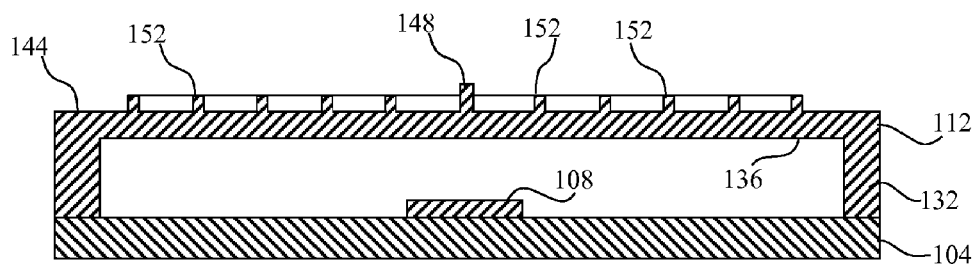


FIG. 11

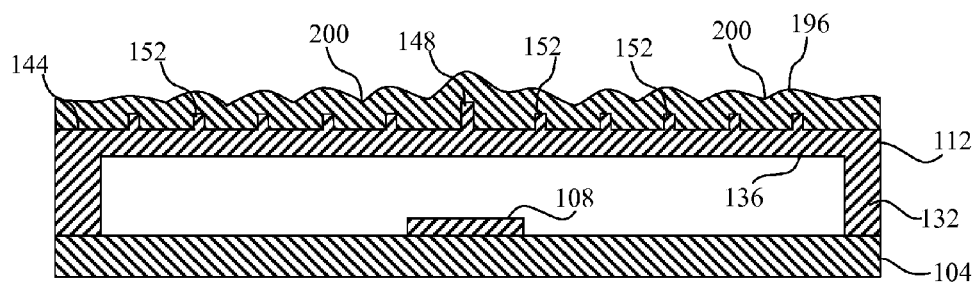


FIG. 12

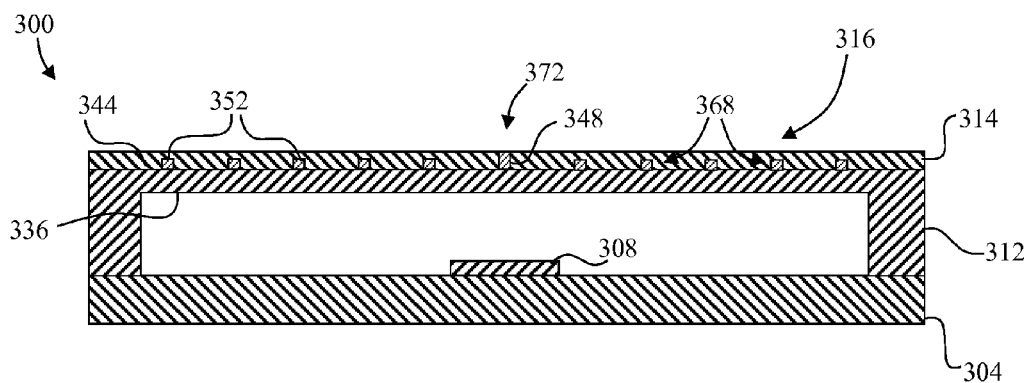


FIG. 13

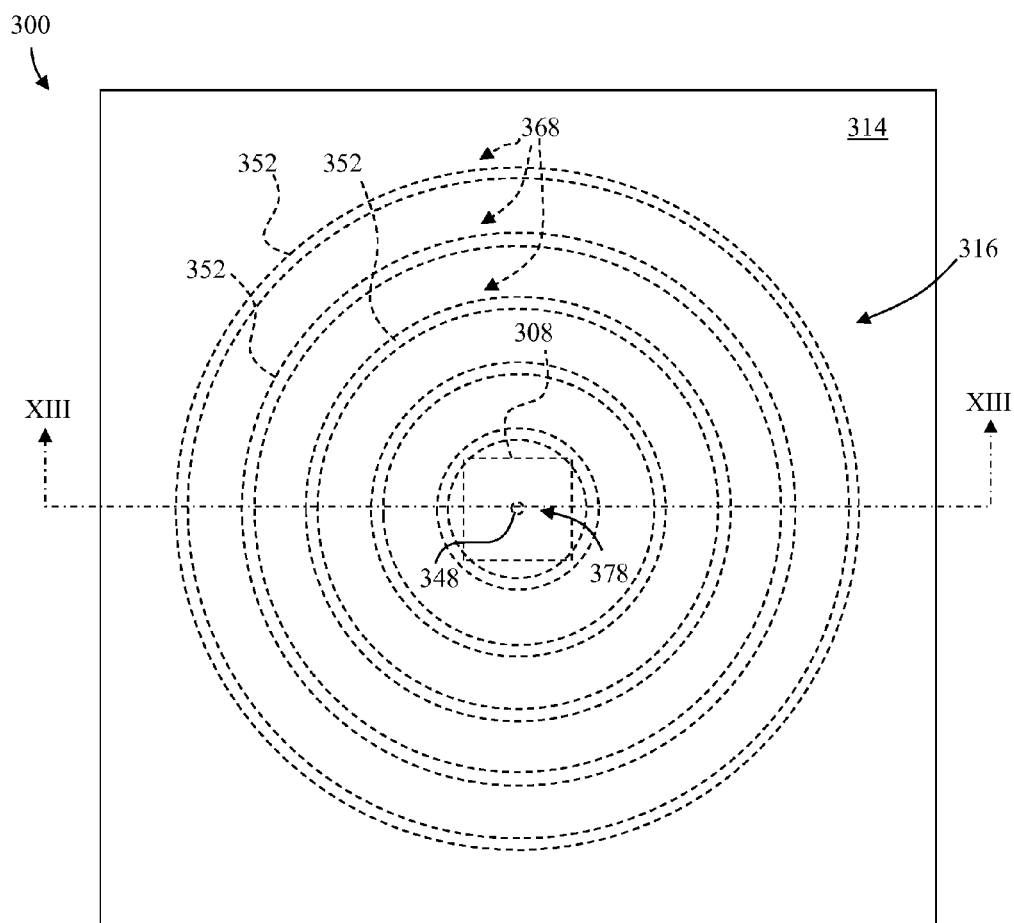


FIG. 14

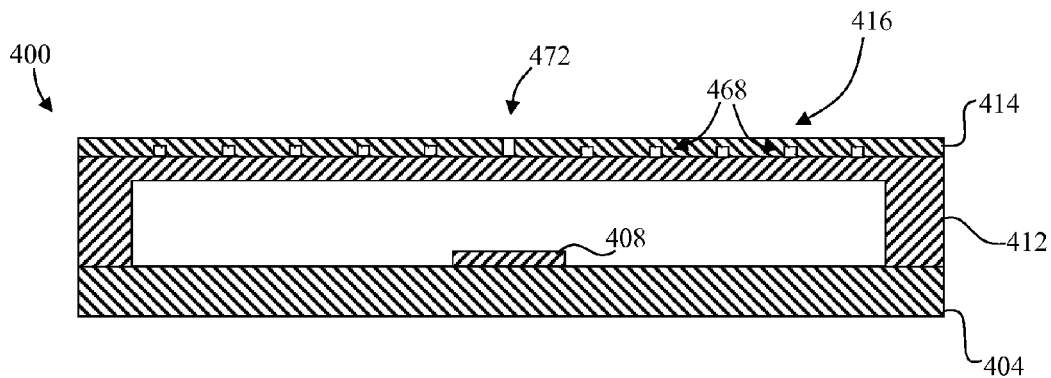


FIG. 15

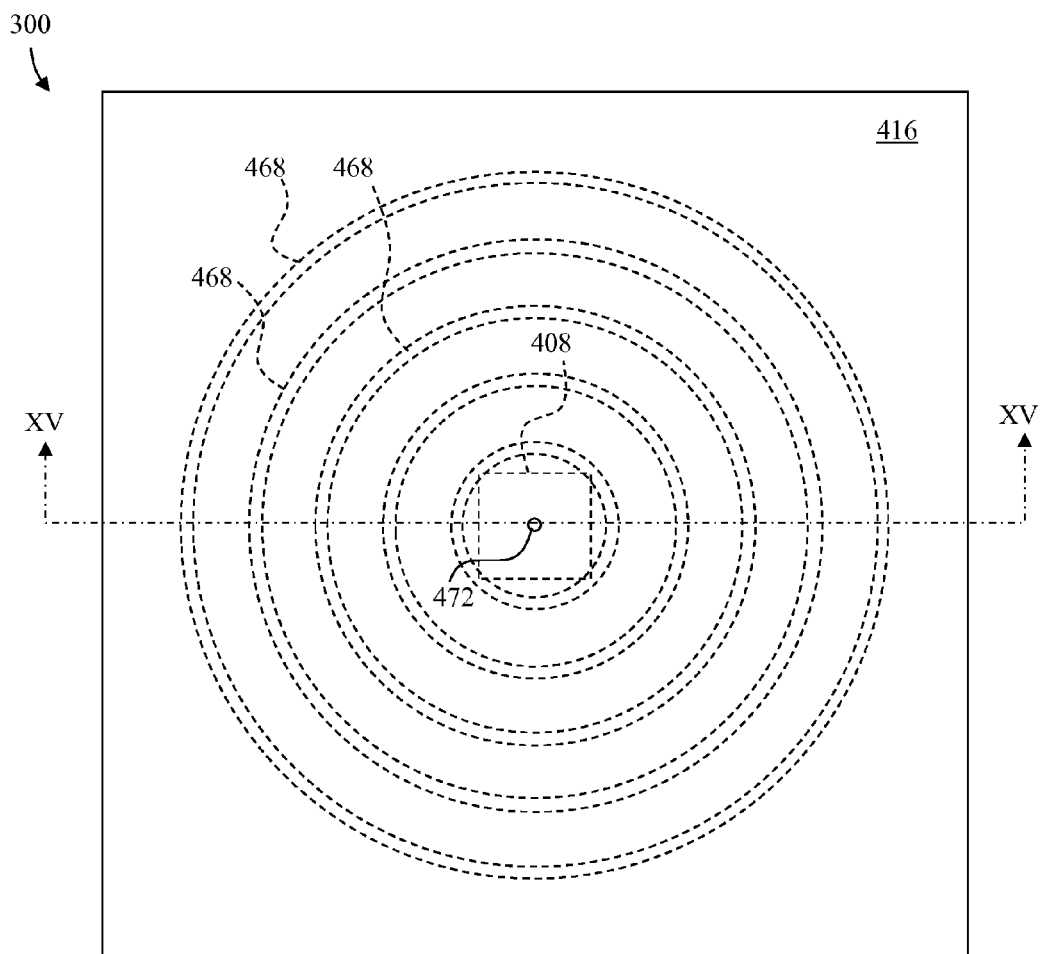


FIG. 16

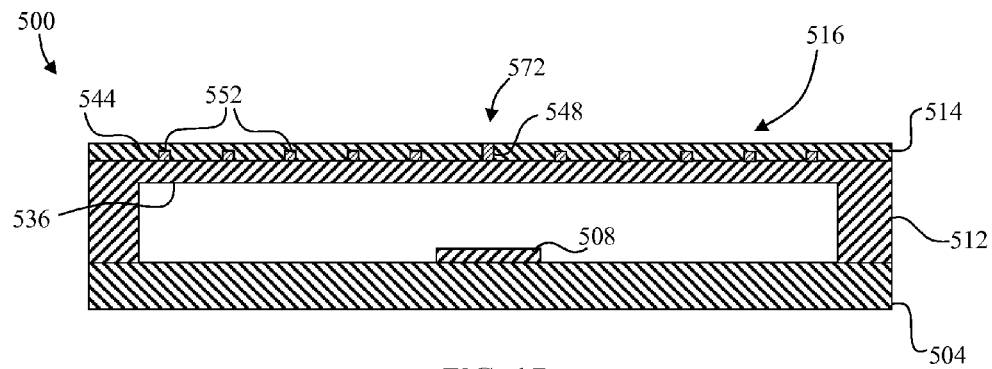


FIG. 17

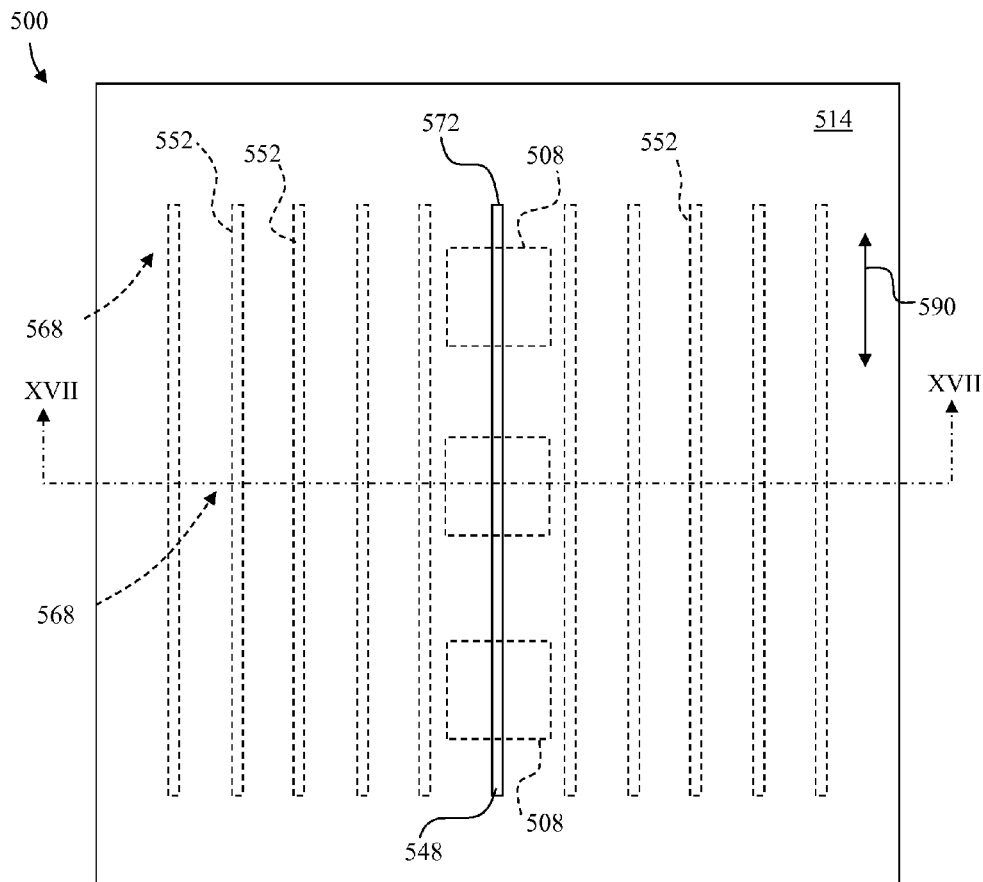


FIG. 18

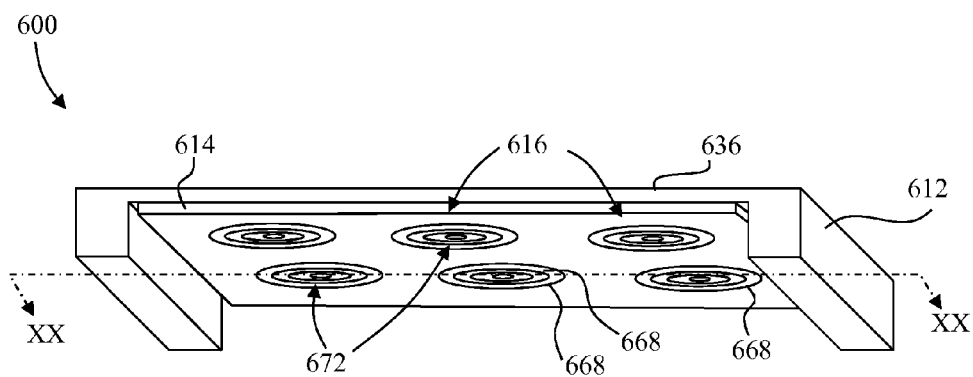


FIG. 19

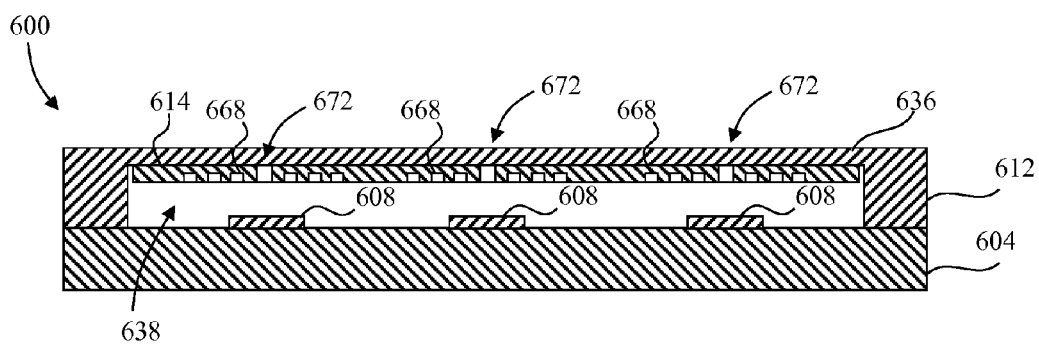


FIG. 20

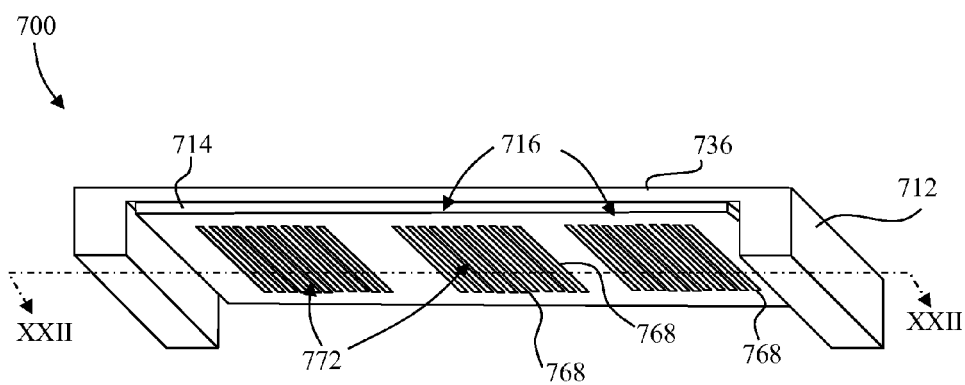


FIG. 21

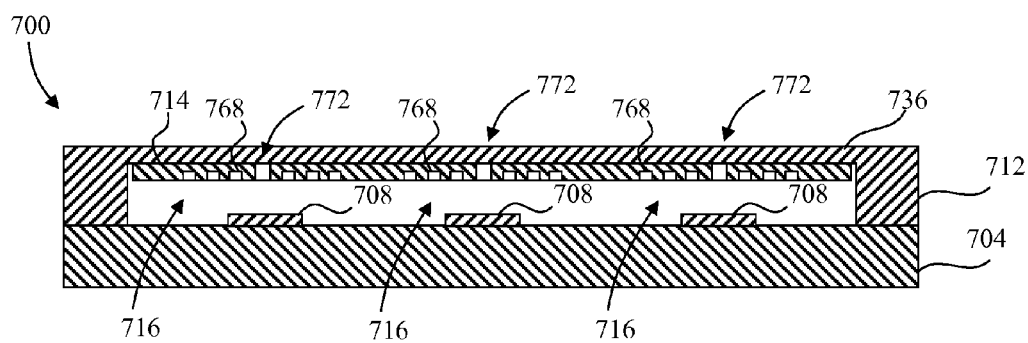


FIG. 22

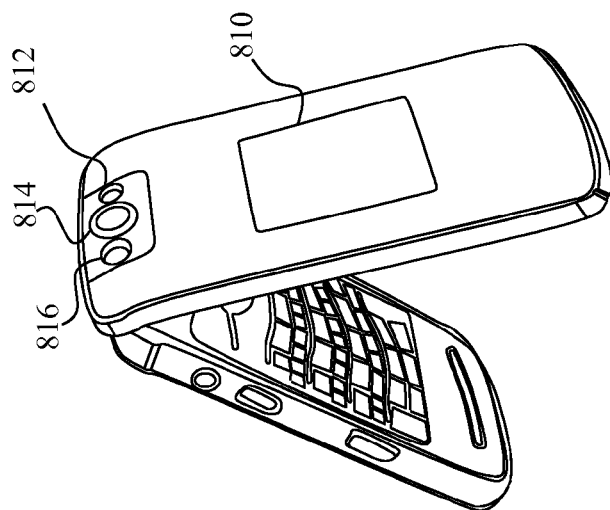


FIG. 24

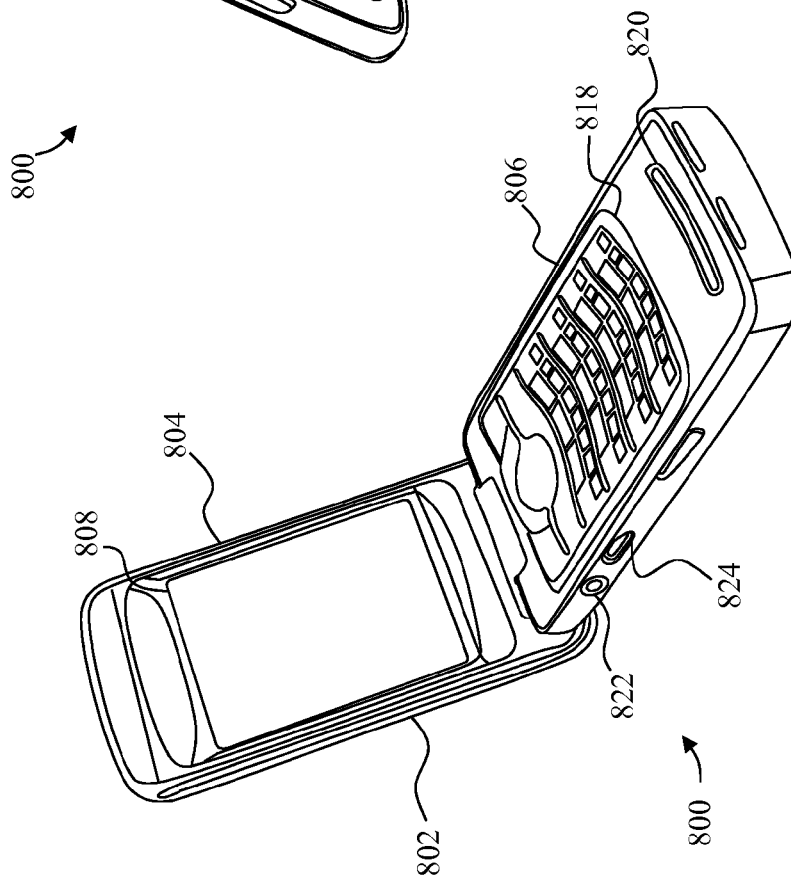
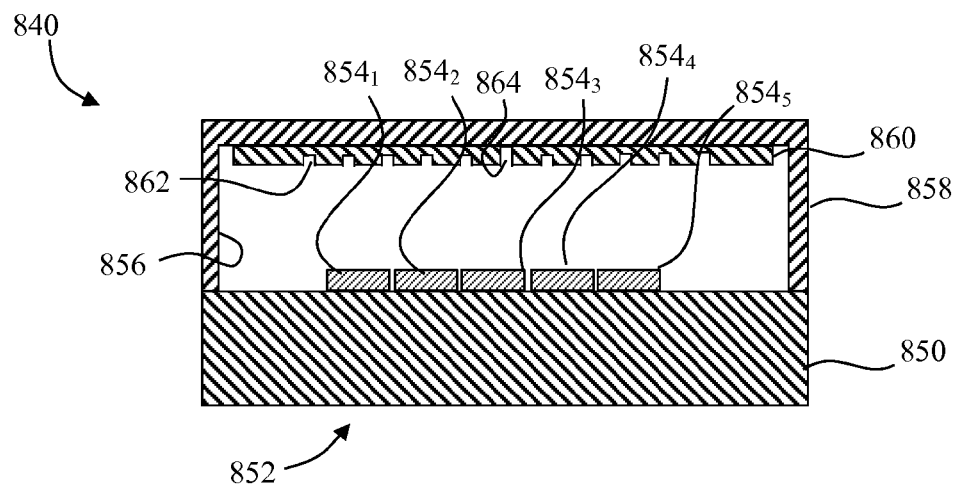
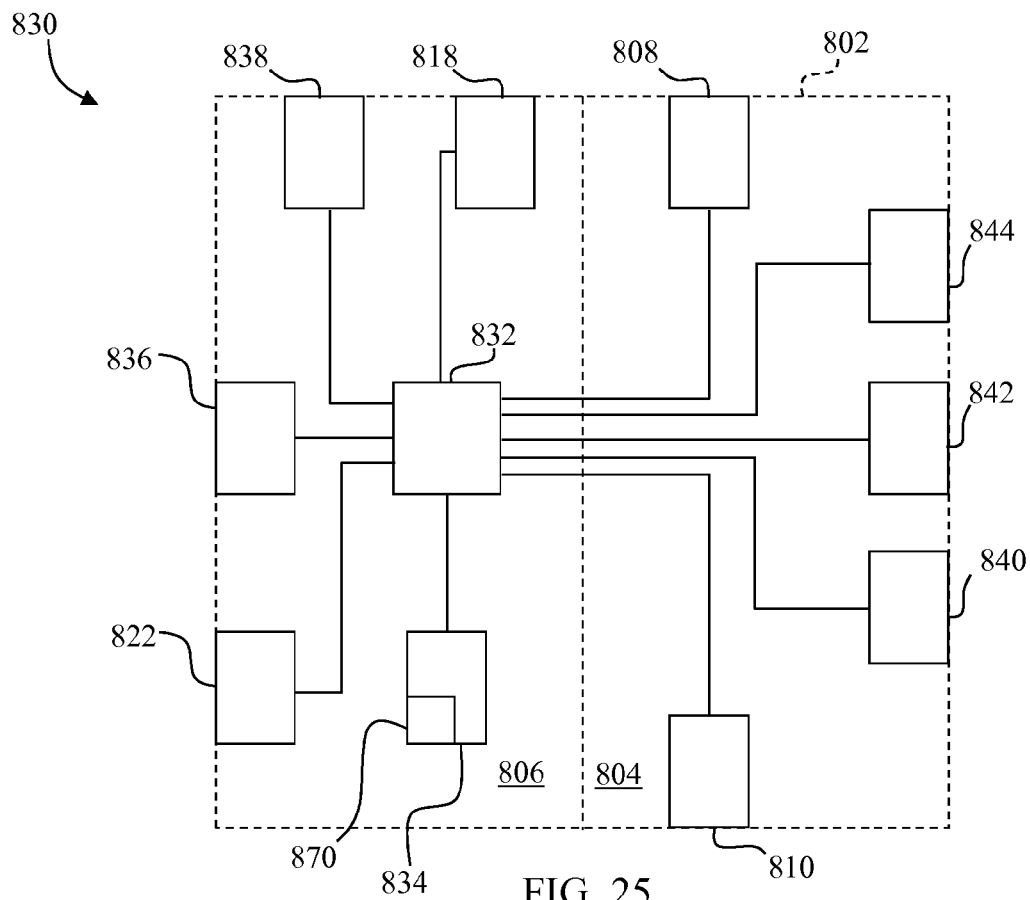


FIG. 23



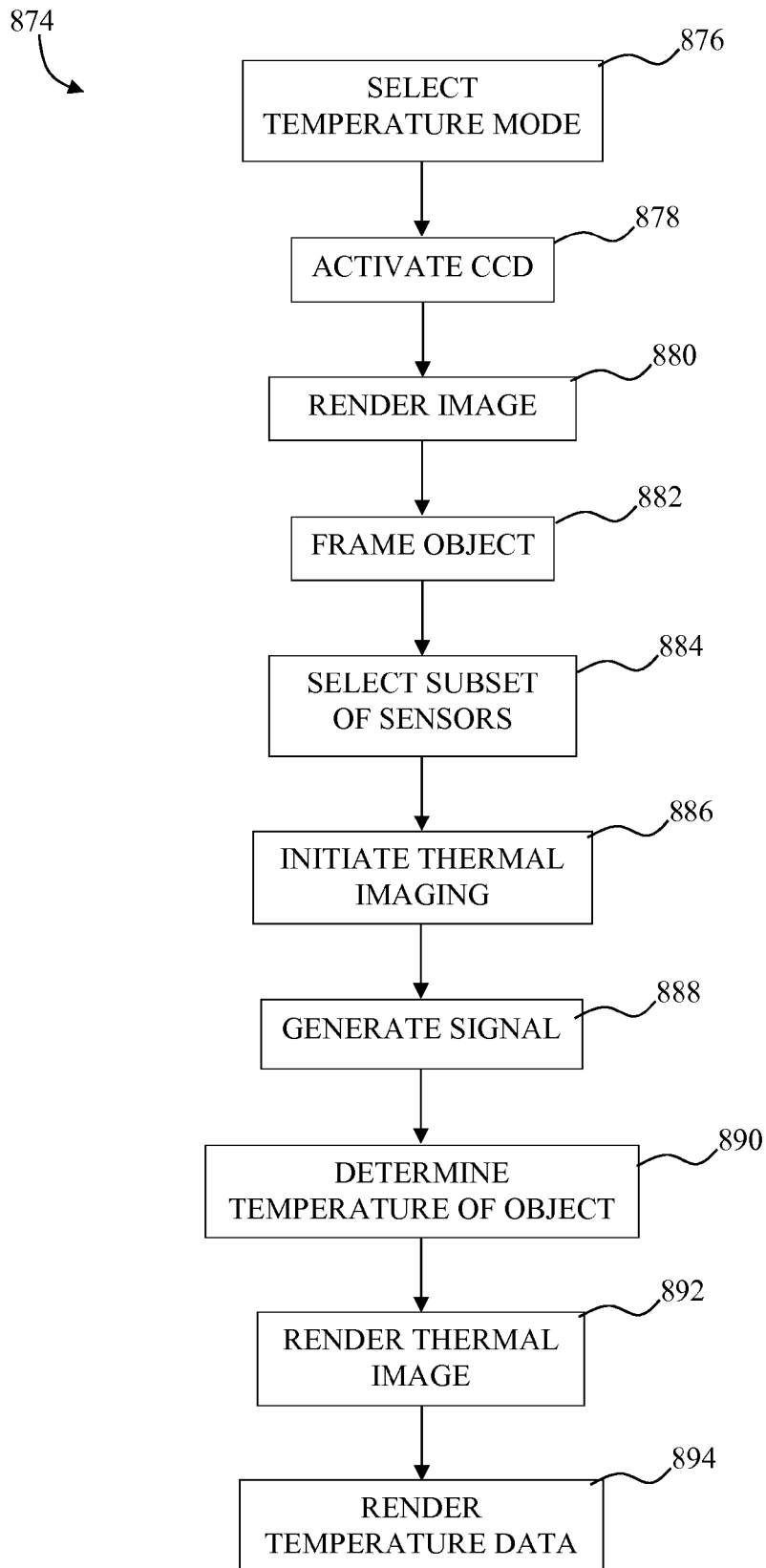


FIG. 27

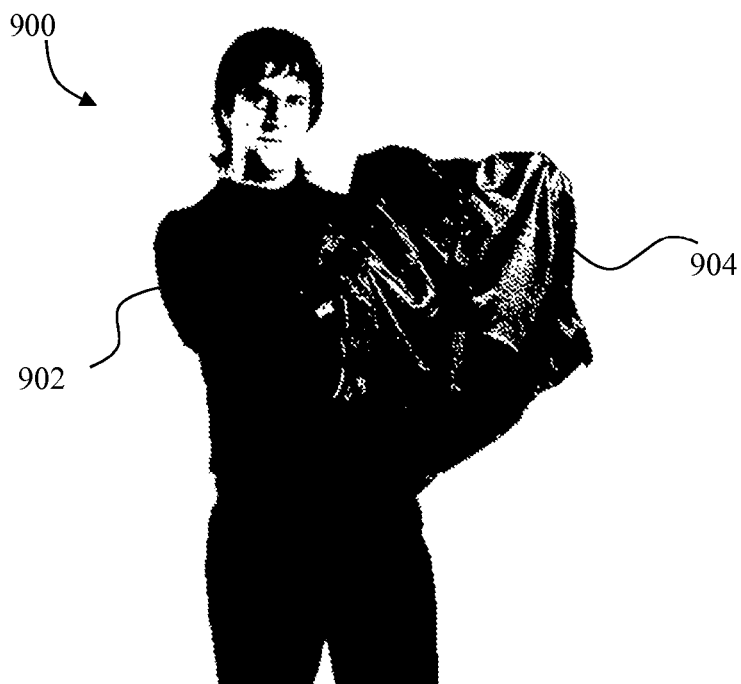


FIG. 28

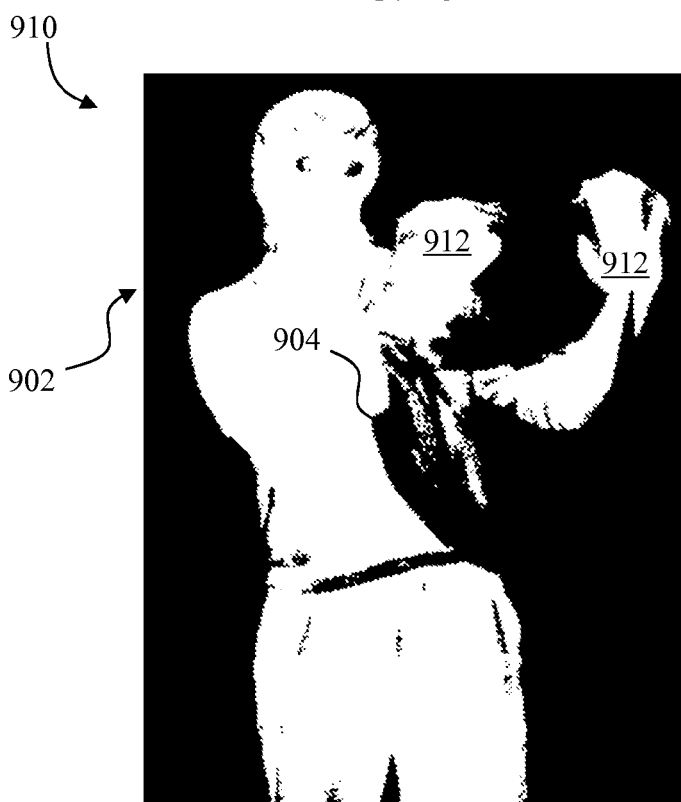


FIG. 29

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MEMS INFRARED SENSOR INCLUDING A PLASMONIC LENS

This application claims priority under 35 U.S.C. §119 to U.S. Provisional Application No. 61/745,571, filed on Dec. 22, 2012, and is a continuation-in-part of U.S. application Ser. No. 14/091,550, filed on Nov. 27, 2013, which claims priority under 35 U.S.C. §119 to U.S. Provisional Application No. 61/731,995, filed on Nov. 30, 2012, the disclosures of which are each incorporated herein by reference in their entirety.

FIELD

This disclosure relates generally to semiconductor sensor devices and methods of fabricating such devices.

BACKGROUND

Infrared radiation (IR) sensors are used in a variety of applications to detect infrared radiation and to provide an electrical output that is a measure of the infrared radiation incident thereon. IR sensors typically use either photonic detectors or thermal detectors for detecting the infrared radiation. Photonic detectors detect incident photons by using the energy of the photons to excite charge carriers in a material. The excitation of the material is then detected electronically. Thermal detectors also detect photons. Thermal detectors, however, use the energy of the photons to increase the temperature of a component. By measuring the change in temperature, the intensity of the photons producing the change in temperature can be determined.

Photonic detectors typically have higher sensitivity and faster response times than thermal detectors. However, photonic detectors must be cryogenically cooled in order to minimize thermal interference, thus increasing the cost, complexity, weight, and power consumption of the device. In contrast, thermal detectors operate at room temperature, thus avoiding the cooling required by photonic detector devices. As a result, thermal detector devices can typically have smaller sizes, lower costs, and lower power consumption than photonic detector devices.

One type of infrared thermal detector is a bolometer device. A bolometer device includes an absorber element for absorbing infrared radiation, a transducer element that has an electrical resistance that varies with temperature, and a substrate. In use, infrared radiation incident upon the bolometer device is absorbed by the absorber element, and the heat generated by the absorbed radiation is transferred to the transducer element. As the transducer element heats in response to the absorbed radiation, the electrical resistance of the transducer element changes in a predetermined manner. By detecting changes in the electrical resistance, a measure of the incident infrared radiation can be obtained.

Bolometer devices must first absorb incident infrared radiation to induce a change in temperature. Typically, however, infrared radiation is dispersed on the absorber as well as portions of the bolometer device that are not configured to absorb infrared radiation, such as the substrate. Accordingly, the efficiency of the bolometer device is less than 100% since the absorber is exposed to only a portion of the incident infrared radiation.

It would be desirable to focus the infrared radiation onto the absorber using a focusing device. Known devices for focusing infrared radiation, however, are very expensive and are typically made using germanium. Furthermore, the cost of known focusing devices for infrared radiation typically

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exceeds the cost of the bolometer by at least an order of magnitude. Accordingly, while known bolometer devices are effective, there is a constant need to increase the efficiency of bolometer devices, simplify the fabrication, and/or to decrease the production cost of such devices.

SUMMARY

According to an exemplary embodiment of the disclosure, a semiconductor device includes a substrate, a cap wafer, an absorber, and a lens layer. The substrate defines an upper surface. The cap wafer is supported by the substrate and includes a cap layer spaced apart from the substrate. The absorber extends from the upper surface and is located between the substrate and the cap layer. The lens layer is supported by the cap layer. The lens layer defines a plurality of grooves and an opening located over the absorber.

According to another exemplary embodiment of the disclosure, a method of fabricating a semiconductor device includes forming an absorber on a substrate, and supporting a cap layer over the substrate to define a cavity between the substrate and the cap layer in which the absorber is located. The method further includes forming a lens layer on the cap layer. The lens layer is spaced apart from the cavity and defines a plurality of grooves and an opening located over the absorber.

A portable thermal imaging system in a further embodiment includes a portable housing configured to be carried by a user, a bolometer sensor assembly supported by the housing and including an array of thermal sensor elements and at least one plasmonic lens, a memory including program instructions, and a processor operably connected to the memory and to the sensor, and configured to execute the program instructions to obtain signals from each of a selected set of thermal sensor elements of the array of thermal sensor elements, assign each of the obtained signals with a respective color data associated with a temperature of a sensed object, and render the color data.

A method of operating a portable thermal imaging system includes providing a portable housing configured to be carried by a user, supporting a bolometer sensor assembly with the housing, the bolometer sensor assembly including an array of thermal sensor elements and at least one plasmonic lens, obtaining signals from each of a selected set of thermal sensor elements of the array of thermal sensor elements with a processor, assigning each of the obtained signals with a respective color data associated with a temperature of a sensed object, and rendering the color data.

BRIEF DESCRIPTION OF THE DRAWINGS

The above-described features and advantages, as well as others, should become more readily apparent to those of ordinary skill in the art by reference to the following detailed description and the accompanying figures in which:

FIG. 1 is a perspective view of a prior art bolometer pixel of a bolometer device;

FIG. 2 is a perspective view of a prior art bolometer device including a plurality of the bolometer pixels of FIG. 1 formed on a substrate;

FIG. 3 is a perspective view of the bolometer device of FIG. 2 including a cap wafer formed on the substrate over the plurality of bolometer pixels;

FIG. 4 is a side cross sectional view of a semiconductor sensor device, as described herein, taken along line IV-IV of FIG. 5, the semiconductor sensor device including a bolom-

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eter pixel and a lens structure defining a plurality of concentric grooves and an IR opening;

FIG. 5 is a top plan view of the semiconductor sensor device of FIG. 4, showing the plurality of concentric grooves and the bolometer pixel in broken lines;

FIG. 6 is a side cross sectional view taken along a line similar to the line IV-IV of FIG. 5, showing a substrate, a bolometer pixel, and a cap wafer;

FIG. 7 is a side cross sectional view taken along a line similar to the line IV-IV of FIG. 5, showing a plurality of concentric grooves formed in a first portion of a sacrificial layer applied to the cap wafer;

FIG. 8 is a side cross sectional view taken along a line similar to the line IV-IV of FIG. 5, showing material of the cap wafer deposited into the concentric grooves formed in the first portion of the sacrificial layer;

FIG. 9 is a side cross sectional view taken along a line similar to the line IV-IV of FIG. 5, showing a second portion of the sacrificial layer including a post opening formed completely through the sacrificial layer;

FIG. 10 is a side cross sectional view taken along a line similar to the line IV-IV of FIG. 5, showing material of the cap wafer deposited into the post opening;

FIG. 11 is a side cross sectional view taken along a line similar to the line IV-IV of FIG. 5, showing a plurality of concentric ridges and a center post after removal of the sacrificial layer;

FIG. 12 is a side cross sectional view taken along a line similar to the line IV-IV of FIG. 5, showing material of the lens structure deposited over the plurality of concentric ridges and the center post;

FIG. 13 is a side cross sectional view of another embodiment of a semiconductor sensor device, as described herein, taken along line XIII-XIII of FIG. 14, the semiconductor sensor device including a bolometer pixel and a lens structure defining a plurality of concentric grooves and an IR opening;

FIG. 14 is a top plan view of the semiconductor sensor device of FIG. 13, showing the plurality of concentric grooves and the bolometer pixel in broken lines;

FIG. 15 is a side cross sectional view of another embodiment of a semiconductor sensor device, as described herein, taken along line XV-XV of FIG. 16, the semiconductor sensor device including a bolometer pixel and a lens structure defining a plurality of concentric grooves and an IR opening;

FIG. 16 is a top plan view of the semiconductor sensor device of FIG. 15, showing the plurality of concentric grooves and the bolometer pixel in broken lines;

FIG. 17 is a side cross sectional view of another embodiment of a semiconductor sensor device, as described herein, taken along line XVII-XVII of FIG. 18, the semiconductor sensor device including a plurality of bolometer pixels and a lens structure defining a plurality of linear grooves and an IR opening;

FIG. 18 is a top plan view of the semiconductor sensor device of FIG. 17, showing the plurality of linear grooves and the plurality of bolometer pixels in broken lines;

FIG. 19 is a perspective view of an embodiment of a semiconductor sensor device, as described herein, that includes a lens layer formed on an underside of a cap wafer, the lens layer is shown as defining six lens structures;

FIG. 20 is a side cross sectional view taken along the line XX-XX of FIG. 19;

FIG. 21 is a perspective view of an embodiment of a semiconductor sensor device, as described herein, that

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includes a lens layer formed on an underside of a cap wafer, the lens layer is shown as defining three lens structures; and

FIG. 22 is a side cross sectional view taken along the line XXII-XXII of FIG. 21;

FIGS. 23 and 24 depict perspective views of one embodiment of a portable device in which the subject disclosure is used;

FIG. 25 depicts a block diagram of the components of the portable device of FIG. 23;

FIG. 26 depicts a side cross-sectional view of the sensor assembly of FIG. 25;

FIG. 27 depicts a procedure for obtaining data for obtaining a thermal image and determining the temperature of an object using the portable device of FIGS. 23 and 24;

FIG. 28 depicts the display of FIG. 23 wherein data from a CCD is rendered on the display; and

FIG. 29 depicts the display of FIG. 23 wherein data from the bolometer array is rendered on the display.

DETAILED DESCRIPTION

For the purpose of promoting an understanding of the principles of the disclosure, reference will now be made to the embodiments illustrated in the drawings and described in the following written specification. It is understood that no limitation to the scope of the disclosure is thereby intended. It is further understood that this disclosure includes any alterations and modifications to the illustrated embodiments and includes further applications of the principles of the disclosure as would normally occur to one skilled in the art to which this disclosure pertains.

As shown in FIG. 1, a prior art micro electromechanical system (MEMS) bolometer pixel 10 includes an absorber 14 and two legs 18, 22. The absorber 14 is configured to undergo an electrical change in response to absorbing infrared radiation 24 (shown schematically as a downward pointing arrow and also referred to herein as “radiation” and “IR”). When the absorber 14 is exposed to the IR 24 emitted from an object (not shown), the absorber heats up and undergoes, for example, a change in electrical resistance, which is detected using an external electrical circuit (not shown). The exemplary absorber 14 is shown as being a substantially planar rectangular element. In another embodiment, however, the absorber 14 has any desired shape and/or configuration.

The legs 18, 22 extend from the absorber 14 and are configured to be electrically connected to the external electrical circuit that monitors the electrical state of the absorber 14. In one embodiment, the external circuit is configured to generate an output that represents a temperature based on an electrical resistance of the absorber 14, as measured from the leg 18 to the leg 22.

The bolometer pixel 10, including the absorber 14 and the legs 18, 22, is typically formed from an ultra-thin layer (approximately 10 nm), of metal. Exemplary metals include, but are not limited to, vanadium oxide, platinum, and titanium. In another embodiment, the bolometer pixel 10 is formed from any desired material.

As shown in FIG. 2, a plurality of the bolometer pixels 10 is arranged in a focal plane array on a substrate 28. The substrate 28 is substantially planar and is also referred to herein as a “reflector” and a “reflector layer.” The substrate 28 is typically formed from silicon using CMOS technology, but may be formed/made using any desired material and technology.

FIG. 3 shows a typical prior art bolometer sensor assembly 34 that includes the substrate 28, the plurality of bolom-

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eter pixels **10**, and a cap wafer **38**. The cap wafer **38** extends from the substrate **28** and defines a cap layer **42** that is spaced apart from the bolometer pixels **10** by a distance **46**. In one embodiment, the cap wafer **38** is formed from undoped or lowly doped silicon; however, the cap wafer may be formed from any desired material that is at least partially transparent to the IR **24**.

The bolometer sensor assembly **34** is shown in FIG. **3** as being exposed to infrared radiation **24** that is emitted by an object (not shown). The cap wafer **38** passes most of the IR **24** through to the pixels **10**. Specifically, the material of the cap wafer **38** transmits about 60% to 70% of the IR **24** through the cap layer **42**. When the IR **24** passes through the cap wafer **38** it is dispersed across the pixels **10** and the substrate **28**. The percentage of the IR **24** that is incident on portions of the bolometer sensor assembly **34** other than the bolometer pixels **10** is generally not used to determine the temperature of the object. This leads to an inherent inefficiency of the prior art bolometer sensor assembly **34**, since only a portion of the available IR **24** is used to heat the bolometer pixels **10**.

As shown in FIG. **4**, a bolometer sensor assembly **100**, which is a semiconductor sensor device, includes a substrate **104**, a plurality of bolometer pixels **108** (only one of which is shown), a cap wafer **112**, and a lens layer **114**. Infrared radiation (IR) **120** is shown as being incident on the bolometer sensor assembly **100**. The lens layer **114** includes a plurality of plasmonic lens structures **116** (only one of which is shown) that are configured to focus/beam the IR **120** into an IR ray **124** that is incident directly onto the pixel **108**, thereby significantly increasing the efficiency of the bolometer sensor assembly **100**.

The substrate **104** is substantially planar and is also referred to herein as a “reflector” or a “reflector layer.” The substrate **104** is typically formed from silicon using CMOS technology, but may be formed/made using any desired material and technology including silicon on insulator (SOI) technology.

The bolometer pixel **108**, which is also referred to herein as an “absorber,” is substantially identical to the bolometer pixel **10** of FIG. **1**. In another embodiment, the bolometer pixel **108** is provided as any type of bolometer pixel as desired. The bolometer pixel **108** extends from an upper surface **128** of the substrate **104**.

The cap wafer **112** is supported by the substrate **104** and includes a support structure **132** and a cap layer **136**. The support structure **132** extends upward from the upper surface **128** of the substrate **104**. The cap layer **136** extends from the support structure **136** and is spaced apart from the substrate **104** by a distance **140**, such that a cavity **138** is defined between the upper surface **128** of the substrate and a lower surface **142** of the cap layer **136**. The bolometer pixel **108** is located between the substrate **104** and the cap layer **136** and is at least partially located in the cavity **138**. The cap layer **136** is substantially parallel to the substrate **104**.

In one embodiment, the cap wafer **112** is formed from undoped or lowly doped silicon; however, the cap wafer may be formed from any desired material that is at least partially transparent to the IR **120**. Furthermore, in some embodiments, the support structure **132** and the cap layer **136** are formed from different materials.

A post **148** and a plurality of ridges **152** are formed on an upper surface **144** of the cap layer **136**. The post **148**, which is also referred to herein as pillar, is a substantially cylindrical protuberance that extends upward (as shown in FIG. **4**), away from the upper surface **144** of the cap layer **136** for a post distance **156**. An exemplary post distance **156** is

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approximately 2.5 micrometers (2.5 μm). The post **148** defines a diameter of approximately 400 nanometers (400 nm). In another embodiment, the post **148** is any desired size and shape, such as square, rectangular, triangular, or any other desired shape including irregular shapes.

With additional reference to FIG. **5**, the ridges **152** are substantially circular and are concentrically arranged on the upper surface **144** of the cap layer **136**. The ridges **152**, as well as the bolometer pixel **108**, are shown in phantom in FIG. **5** since they are located below the lens layer **114** as viewed from above. The cap layer **136** includes five of the ridges **156**, but in other embodiments the cap layer includes any desired number of ridges. Each ridge **156** extends upward (as shown in FIG. **4**), away from the upper surface **144** of the cap layer **136** for a ridge distance **160** that is less than the post distance **156**. In one exemplary embodiment, the ridge distance **160** is approximately one micrometer (1 μm). As illustrated, the ridges **152** are approximately evenly spaced apart from each other, but may be unevenly spaced apart in another embodiment. Furthermore, the ridges **152** may have any desired shape and configuration including non-concentric configurations.

The lens layer **114** is supported by the cap layer **136** and, in particular, is located generally above the upper surface **144** of the cap layer in the embodiment of FIG. **4**. The lens layer **114** is referred to as being “generally above” the upper surface **144**, since the post **148** may be considered part of the upper surface **144** and the post extends completely through the lens layer. With such an interpretation, the lens layer **114** is not “completely” above the upper surface **144**, but is “generally above” the upper surface. In the illustrated embodiment, the lens layer **114** is formed on the upper surface **144** of the cap layer **136**; however, in other embodiments, one or more other layers (not shown) may be positioned between the upper surface and the lens layer.

The lens layer **114** defines an upper surface **164** that is substantially planar and an opposite lower surface **176**. The upper surface **164** is spaced apart from the lower surface **176** by approximately the post distance **156**. Accordingly, a thickness of the lens layer **114** is approximately 2.5 micrometers (2.5 μm), in one embodiment.

The lens structure **116** of the lens layer **114** includes a plurality of grooves **168** and an IR opening **172**. The grooves **168** are concentric circular grooves that are centered about the IR opening **172**. The grooves **168** are defined in the lower surface **176** and are complementary in shape and size to the ridges **152** formed in/on the cap layer **136**, such that the grooves are at least partially filled by the ridges (i.e. the material of the cap wafer **112**). In one embodiment, the grooves **168** define a cross sectional area of approximately one square micrometer (1 μm^2) and are spaced apart from each other by approximately five micrometers (5 μm). The lens structure **116** includes the same number of grooves **168** as the number of ridges **152**. Accordingly, the lens structure **116** includes five of the grooves **168** in the exemplary embodiment. The grooves **168** define a depth **178** that is less than the thickness of the lens layer **114**.

With continued reference to FIG. **4**, the IR opening **172**, which is also referred to herein as an opening, a circular opening, an aperture opening, and an aperture, extends completely through the thickness of the lens layer **114**, unlike the grooves **168**. The IR opening **172** is positioned at approximately the center of each of the grooves **168**, as shown in FIG. **5**, and is located over the bolometer pixel **108**. The IR opening **172** is complementary in shape and size to the post **148** and is substantially/completely filled with the post. The IR opening **172** and the post **148** are configured to

be exposed to the IR 120. Depending on the configuration of the lens structure 116, the IR opening 172 may pass electromagnetic radiation outside of the infrared range.

The lens layer 114 may be formed from a “perfectly conducting material” (PCM) that is configured to prevent the passage of IR therethrough. The PCM has zero electrical resistance (i.e. is a perfect conductor) and is configured to block 100% of the IR 120 incident thereon. Accordingly, suitable materials for forming the lens layer 114 include metal, such as platinum, metallic alloys, and the like.

As shown in FIG. 6, a method of fabricating the bolometer sensor assembly 100 includes providing the substrate 104. Next, the bolometer pixel 108 is formed on the upper surface 128 of the substrate 104 according to any desired process. After formation of the bolometer pixel 108, the cap wafer 112 is applied/formed on the substrate 104 using any process.

Next, with reference to FIG. 7, a first portion of a sacrificial layer 180 is deposited on the upper surface 144 of the cap layer 136. The sacrificial layer 180 defines a thickness approximately equal to the ridge distance 160 (FIG. 4). The sacrificial layer 180 is formed from any suitable material.

The method further includes applying/depositing/forming/printing a mask (not shown) on the sacrificial layer 180. The mask is a resist mask, a photo mask, or the like. The mask is applied in a pattern that corresponds to the desired configuration of the ridges 152, but does not typically account for the post 148 (in this exemplary embodiment). The sacrificial layer 180 is etched through the mask to form a plurality of concentric grooves 184. The grooves 184 are complimentary in size and shape to the ridges 152.

As shown in FIG. 8, next the material of the cap wafer 112 is deposited into the grooves 184 to form the ridges 152. After the depositing, the ridges 152 and the sacrificial layer 180 may be polished using chemical and mechanical polishing (CMP) or any other desired smoothing/polishing process.

With reference to FIG. 9, a second portion of the sacrificial layer 180 is formed over the ridges 152. Then, another mask (not shown) is applied to the sacrificial layer 180 in a pattern that corresponds to the desired configuration of the post 148. Afterwards, the sacrificial layer 180 is etched to form a post opening 188 that extends through the sacrificial layer.

In FIG. 10, material of the cap wafer 112 is deposited into the post opening 188 to form the post 148. Next, as shown in FIG. 11, the sacrificial layer 180 is etched away, using any desired process. Removal of the sacrificial layer 180 exposes the post 148, the ridges 152, and the upper surface 144 of the cap layer 136.

According to FIG. 12, a conformal layer 192 of the material of the lens layer 114 (FIG. 4) is deposited onto the upper surface 144 of the cap layer 136, the post 148, and the ridges 152. In the illustrated embodiment, the conformal layer 192 is formed using a predetermined number of cycles of atomic layer deposition (ALD). The conformal layer 192 includes a plurality of curved surfaces 196 and valleys 200. The valleys 200 correspond approximately to a midpoint between the ridges 152. An apex of the curved surfaces 196 corresponds to the location of the ridges 152. The valleys 200 and the curved surfaces 196 are a consequence of the layered formation of the conformal layer 192. In another embodiment the material of the lens structure 116 is deposited using any desired process including sputtering and evaporative techniques.

Next, with further reference to FIG. 4, the conformal layer 192 is smoothed using CMP or another desired process to arrive at the smooth and flat upper surface 164 of the lens structure 116. The polishing step removes a portion of the conformal layer 192 that is in contact with a post upper surface 204, thereby uncapping the IR opening 172. After polishing, the ridges 152, however, remain buried below the upper surface 164 of the lens layer 114 and are not directly exposed to the IR 120.

In operation, the lens structure 116 focuses and/or to beams the IR 120 into an IR ray 124 that is directed onto an absorber (see, e.g., absorber 14, FIG. 1) of the bolometer pixel 108. With continued reference to FIG. 4, when the lens layer 114 is exposed to the IR 120, the lens structure 116 enables the IR to pass through the IR opening 172, but blocks the passage of the IR through all other areas of the lens layer 114. As a result of the size and shape of the grooves 168 (among other factors), the IR 120 that passes through the IR opening 172 is emitted as the focused ray of IR 124. The IR ray 124 passes through the cap layer 136 and is incident on the pixel 108. Accordingly, the lens structure 116 functions as a plasmonic lens that is configured to focus the IR 120 onto the pixel 108 instead of allowing the IR to be scattered across the substrate 104 as in the prior art bolometer sensor assembly 34 of FIG. 3. Additionally, the lens structure 116 results in more efficient absorption of the IR 120 by the pixel 108 and a higher responsivity from the sensor device 100.

The lens structure 116 is configurable to pass a particular wavelength of electromagnetic radiation therethrough, typically in the infrared range. In particular, the wavelength of electromagnetic radiation that passes through the IR opening 172 is dependent on the shape of the opening 172, the diameter of the opening 172, the number of the grooves 168, and the size of the grooves 168 (width and depth), among other factors. In general, the efficiency of the lens structure 116 increases as the incoming electromagnetic radiation approximates the target wavelength of the lens. In this way, the lens structure 116 is configurable to be sensitive to a particular wavelength or a range of wavelengths, instead of being sensitive to all wavelengths of electromagnetic radiation in general. In one embodiment, the bolometer sensor assembly 100 includes a lens layer 114 having a plurality of differently configured lens structures 116 to enable the semiconductor device to be sensitive to more than one desired wavelength or more than one range of wavelengths.

As shown in FIGS. 13 and 14, another embodiment of a bolometer sensor assembly 300 includes a substrate 304, a plurality of bolometer pixels 308 (only one of which is shown), a cap wafer 312, and a plurality of lens structures 316 (only one of which is shown) formed in a lens layer 314. A post 348 and a plurality of ridges 352 are formed on an upper surface 344 of a cap layer 336 of the cap wafer 312. The lens structure 316 defines an aperture 372 in which the post 348 is located, and a plurality of grooves 368 that is substantially/completely filled with the ridges 352.

The bolometer sensor assembly 300 is substantially identical to the bolometer sensor assembly 100, except that the post 348 and the ridges 352 are formed from a material that is different than the material of the cap wafer 312. The material of the post 348 and the ridges 352 is deposited into trenches formed in a sacrificial layer (See e.g. grooves 184 formed in the sacrificial layer 180 of FIG. 8) using any commonly used deposition technique including evaporation, sputtering, and ALD among others.

The post 348 and the ridges 352 may be formed from a material having a refractive index that is close to the

refractive index of air. The wavelength of the electromagnetic radiation (typically IR) that the lens structure 316 is configured to efficiently focus through the aperture 372 is based on the material from which the post 348 and the ridges 352 is formed. Accordingly, by selecting a material with a particular index of refraction the lens structure 316 is “tuned” to a desired wavelength of electromagnetic radiation.

As shown in FIGS. 15 and 16, another embodiment of a bolometer sensor assembly 400 includes a substrate 404, a plurality of bolometer pixels 408 (only one of which is shown), a cap wafer 412, and a plurality of lens structures 416 (only one of which is shown). The lens structure 416 defines an aperture 472 and a plurality of grooves 468.

The bolometer sensor assembly 400 is substantially identical to the bolometer sensor assembly 100, except that the bolometer sensor assembly 400 does not include a post 148 or the ridges 152. Instead, the grooves 468 and the aperture 472 are gas-filled/air-filled voids. The type of gas(es) in the gas-filled 468, 472 voids is selectable to have a desired index of refraction to enable “tuning” of the lens structure 416.

In one embodiment, the grooves 468 and the aperture 472 of the bolometer sensor assembly 400 are formed similarly to the grooves 168 and the IR opening 172 of the semiconductor device 100. Instead of forming the post 148 and the ridges 152 from the material of cap wafer 112, however, the post 148 and the ridges 152 are formed from a thermally decomposable sacrificial polymer such as “Unity” or a photo-definable material. The thermally decomposable material of the post 148 and the ridges 152 is deposited using any commonly used deposition technique including evaporation, sputtering, and atomic layer deposition among others. A thermally decomposable sacrificial polymer is a material that is selectively removable from the bolometer sensor assembly 100 in response to being heated to a predetermined temperature. The bolometer sensor assembly 400 is heated to approximately 300 to 400 degrees Celsius, for example, in order to evaporate/decompose the thermally decomposable sacrificial polymer. Upon being heated, the thermally decomposable sacrificial polymer evaporates through the material of the lens structure 416 and/or through the material of the cap wafer 412. Evaporation of the material of the post 148 and the ridges 152 leaves behind the air-filled grooves 468 and the aperture 472.

As shown in FIGS. 17 and 18, another embodiment of a bolometer sensor assembly 500 includes a substrate 504, a plurality of bolometer pixels 508 (only three of which are shown), a cap wafer 512, and lens layer 514 includes a plurality of lens structures 516 (only one of which is shown). An aperture ridge 548 and a plurality of ridges 552 and are formed on an upper surface 544 of a cap layer 536 of the cap wafer 512. The lens structure defines a slit 572 (also referred to herein as an opening, an aperture opening, and an aperture) in which the aperture ridge 548 is located, and a plurality of grooves 568 that is substantially/completely filled with the ridges 552.

The bolometer sensor assembly 500 is substantially identical to the bolometer sensor assembly 100, except that the grooves 568 and the aperture 572 are substantially linear and extend in a slit direction 590 instead of being circular. The lens structure 516 functions substantially similarly as the lens structure 116 to focus/beam the IR (see IR 120 of FIG. 4) onto the bolometer pixels 508.

As shown in FIGS. 19 and 20, another embodiment of a bolometer sensor assembly 600 includes a substrate 604, a plurality of bolometer pixels 608 (only three of which are shown), a cap wafer 612, and a lens layer 614 defining a

plurality of lens structures 616 (only six of which are shown). Each of the lens structures 616 defines an aperture 672 and a plurality of grooves 668.

The bolometer sensor assembly 600 is substantially identical to the bolometer sensor assembly 400, except that the lens layer 614 (and the lens structures 616 formed thereon) is located in a cavity 638 defined between the substrate 604 and a cap layer 636 of the cap wafer 612. Since the lens structures 616 are positioned on an “underside” of the cap layer 636 the IR (see IR 120 of FIG. 4) passes through the cap layer before being focused by the lens structures 616.

As shown in FIGS. 21 and 22, another embodiment of a bolometer sensor assembly 700 includes a substrate 704, a plurality of bolometer pixels 708 (only three of which are shown), a cap wafer 712, and a lens layer 714 defining a plurality of lens structures 716 (only three of which are shown). Each of the lens structures 716 defines a slit-shaped aperture 772 and a plurality of substantially linear grooves 768.

The bolometer sensor assembly 700 is substantially identical to the bolometer sensor assembly 500, except that the lens structures 716 are located between the substrate 704 and a cap layer 736 of the cap wafer 712. Since the lens structures 716 are positioned on an “underside” of the cap layer 736 the IR (see IR 120 of FIG. 4) passes through the cap layer before being focused by the lens structures 716.

While many of the embodiments discussed above depicted and made reference to only one pixel, the single pixel in various embodiments is replaced by an array of pixels. For example, each of the pixel 108, the pixel 308, and the pixel 408, in various embodiments, is provided as an array of pixels. Such an array is provided in some embodiments in a portable device such as the portable device of FIGS. 23 and 24, generally designated 800, which in this embodiment is a cellular telephone. In some embodiments, the portable device is a personal digital assistant, a smart phone, a dedicated sensor device, or other desired portable device. The portable device 800 has a housing 802 that includes an upper housing portion 804 and a lower housing portion 806. An inner display 808 is located on the inner side of the upper housing portion 804 and an outer display 810 is located on the outer side of the upper housing portion 804 as depicted in FIG. 24. The outer side of the upper housing portion 804 further includes a thermal sensor assembly port 812, a camera port 814 and a light port 816.

Referring again to FIG. 23, the lower housing portion 806 includes a keyboard 818 and a microphone port 820. A data port 822 and a charging port 824 are located on the side of the lower housing portion 806.

FIG. 25 depicts a control circuit 830 which is located within the housing 802. The control circuit 830 includes a processor 832 and a memory 834 which in this embodiment are located within the lower housing portion 806. The processor 832 is operably connected to the keyboard 818 and the data port 822. The processor 832 is further operably connected to a power source 836 which is accessed through the charging port 824 and a microphone 838 positioned adjacent to the microphone port 820.

The processor 832 is also operably connected to components in the upper housing portion 804 including the inner display 808 and the outer display 810. The processor 832 is further operably connected to a bolometer sensor assembly 840, a charge coupling device (CCD) 842 and a light 844 which are physically located adjacent to the sensor assembly port 812 and are part of an imaging subsystem, the camera port 814 and the light port 816, respectively.

The bolometer sensor assembly **840** is shown in further detail in FIG. 26. The bolometer sensor assembly **840** includes a substrate **850** and an array **852** of thermal sensors **854₁₋₅**. The array **852** is located within a chamber **856** defined in part by a cap **858**. A plasmonic lens **860** is connected to the underside of the cap **858**. In various embodiments, the location and configuration is provided in the manner described above for the lenses **116**, **316**, **416**, **516**, and **716**. In the embodiment of FIG. 26, the plasmonic lens **860** includes one lens structure which is substantially identical to the plasmonic lens structures **616** of FIG. 19, and focuses and/or beams IR incident on the cap **858**, much like an optical lens focuses and/or beams electromagnetic radiation in the visible spectrum. The plasmonic lens **860** is made of a “perfectly conducting layer”, such as any type of metal, for example.

Like the lenses **616**, the plasmonic lens **860** includes a number of concentric grooves **862** and a central aperture **864**. The plasmonic lens **860** includes in various embodiments from about five up to about 50 concentric grooves **862**, which may also be referred to as surface corrugations. The central aperture **864** is generally circular and extends completely through the plasmonic lens **860**.

The plasmonic lens **860** is connected to the cap wafer **858** with the grooves **862** facing away (i.e. spaced apart from) from the cap wafer. The cap wafer **858**, which is imperforate in this embodiment, does not include an opening aligned with the aperture **864**. Accordingly, visible light does not pass through the cap wafer **858**; however, as described above, most of the IR passes through the cap wafer.

Returning to FIG. 25, within the memory **834** are stored program instructions **870**. The program instructions **870**, which are described more fully below, are executable by the processor **832** and/or any other components as appropriate. The program instructions **870** include commands which, when executed by the processor **832**, cause the portable device **800** to obtain data for use in determining the temperature of an object within a field of view of the sensor assembly **840**.

Referring to FIG. 27, there is depicted a flowchart or a process, generally designated **874**, setting forth an exemplary manner of obtaining data for use in obtaining a thermal image and/or determining the temperature of an object within a field of view of the sensor assembly **840** by executing the program instructions **870** according to the present principles. Initially, a user carrying the portable device **800** opens the housing **802** to the position shown in FIG. 23 and uses the keyboard **818** to place the portable device **800** in temperature imaging mode (block **876**). In embodiments which are configured solely for temperature detection, solely for thermal imaging, or for both thermal detection and imaging, the device may only need to be energized. In embodiments such as the portable device **800**, the display **808** in some embodiments is configured to render a menu which the user uses to activate the temperature detection mode.

Once the portable device **800** is placed in temperature detection mode, the processor **832** controls the CCD **842** to an energized condition (block **878**). In response, the CCD **842** begins to detect incoming energy in any acceptable manner and generates a signal indicative of the sensed energy. The processor **832** receives the generated signal and controls the inner display **808** to render the scene viewed (sensed) by the CCD **842** (block **880**).

Using the rendered image as a guide, the user frames the desired scene/object (block **882**). Framing of the object in some embodiments is accomplished by zooming the display

such that the object fills the display **808**. In other embodiments, a shadow frame overlying the viewed scene is manipulated to frame the object. As the object is framed using the inner display **808**, the processor **832** in some embodiments selects a subset of the thermal sensors **854₁₋₅** in the array **852**. By varying the number of active pixels (each of the thermal sensors **854₁₋₅** is a separate pixel), the field of view (FOV) of the sensor assembly **840** is adjusted to comport with the framing of the object in the display **808** (block **884**). Once the object is framed, the user initiates thermal data acquisition (block **886**) such as by pressing a key in the keyboard **818**. In response, the processor **832** controls the array **852** to generate a respective signal from each of the selected thermal sensors **154₁₋₅** (block **888**).

In some embodiments, the CCD **842** is omitted or not used and the array **852** is used to provide an image. In such embodiments, blocks **878-882** are omitted and the processor **832** or an ASIC included with the device, is configured to generate data that forms an output thermal image. In either embodiment, the ASIC or processor **832** is configured to process the electrical signal(s) generated by each of the bolometer pixels **854**. In particular, based on the resistance of the bolometer pixels **854**, the processor **832** generates data that corresponds to thermal information contained in the focused ray.

Each IR data point is then assigned a color in the visual spectrum based on the intensity of the IR sensed by the corresponding bolometer pixel **854** (or group of bolometer pixels) (block **890**). Typically, “high” intensities of IR receive a light color such as white and “low” intensities of IR receive a dark color such as blue or black. Additionally, each IR data point is assigned a temperature value, which is also based on the intensity of the IR sensed by the corresponding bolometer pixel **854** (or group of bolometer pixels). The visual spectrum data is then rendered (block **892**).

By way of example, FIG. 28 depicts an exemplary image **900** from the CCD **842** rendered on the display **808** at block **880**. In the image **900**, an individual **902** and a bag **904** are visible. FIG. 29 depicts an exemplary image **910** from the array **852** of the same individual **902** rendered on the display **808** at block **892**. As shown in FIG. 29, the output thermal image **910** shows the hands **912** of the individual **902** which are not detectable by the CCD **842**. In the embodiment of FIG. 29, the display **808** is a touchscreen. Consequently, when a user touches the touchscreen display **808**, the processor **832** receives touch input from the display **808** and causes the temperature data associated with the color data which is rendered at a location of the display which was touched to be displayed. Consequently, the temperature data associated with that region of the output thermal image **910** which is touched is displayed (block **894**). Accordingly, the user is able to determine the temperature of a particular portion the image **900** or the image **910** by simply touching the corresponding region of the output thermal image **910** on the touchscreen display **808**.

In one embodiment, the array **852** includes approximately one thousand bolometer pixels **854** positioned on the substrate layer **850** and arranged in a focal plane array (“FPA”). For clarity of viewing, however, only five bolometer pixels **854** are illustrated in FIG. 26. In another embodiment, the array **852** includes between 500 and 100,000 of the bolometer pixels **854**.

The bolometer pixels **854** are arranged on the substrate layer **850** in a position to receive a focused ray from the lens **860**. In one embodiment, the pixels **854** are arranged in a generally rectangular shaped array. In another embodiment, the bolometer pixels **854** are arranged in a differently shaped

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array, such as an array having a shape that matches (at least approximately) the shape of a focused ray incident on the substrate layer **850**. Furthermore, the bolometer pixels **854** may be arranged in an array having any other shape as desired by those of ordinary skill in the art. Additionally, the bolometer pixels are arranged according to a Cartesian coordinate system, such that each bolometer pixel **854** in the focal plane array has a unique address on the substrate layer **850**. In another embodiment, the bolometer pixels **854** are arranged according to any other coordinate system that enables each bolometer pixel to have a unique address on the substrate layer **850**.

While the disclosure has been illustrated and described in detail in the drawings and foregoing description, the same should be considered as illustrative and not restrictive in character. It is understood that only the preferred embodiments have been presented and that all changes, modifications and further applications that come within the spirit of the disclosure are desired to be protected.

What is claimed is:

1. A portable thermal imaging system comprising:
 - a portable housing configured to be carried by a user;
 - a bolometer sensor assembly supported by the housing and including an array of thermal sensor elements and at least one plasmonic lens;
 - a memory including program instructions;
 - a processor operably connected to the memory and to the sensor, and configured to execute the program instructions to
 - obtain signals from each of a selected set of thermal sensor elements of the array of thermal sensor elements,
 - assign each of the obtained signals with a respective color data associated with a temperature of a sensed object, and
 - render the color data; and
 - an imaging subsystem including a display, the imaging subsystem operably connected to the processor, wherein the processor is further configured to execute the program instructions to render indicia of a field of view of the bolometer sensor assembly on the display, wherein the bolometer sensor assembly further comprises:
 - a substrate having an upper surface supporting the array of thermal sensor elements; and
 - a cap wafer supported by the substrate and including a cap layer spaced apart from the substrate, the cap layer supporting the at least one plasmonic lens.
2. The system of claim 1, wherein the processor is further configured to execute the program instructions to:
 - receive touch input from a display upon which the color data is rendered; and
 - render the temperature associated with the color data which is rendered at a location of the display which is touched.
3. The system of claim 1, wherein the portable housing is a portable cellular telephone housing.

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4. The system of claim 1, wherein:
 - the selected set of thermal sensor elements is selected based upon a user input; and
 - the rendered indicia of the field of view is based upon the user input.
5. The system of claim 1, wherein the at least one plasmonic lens comprises:
 - a plurality of grooves in a lens layer, and an opening extending completely through the lens layer.
6. The system of claim 5, wherein the plurality of grooves comprise:
 - a plurality of concentric grooves.
7. The system of claim 6, wherein the opening is a circular opening.
8. The system of claim 6, wherein the lens layer is supported on an upper surface of the cap layer.
9. The system of claim 8, wherein:
 - the cap wafer is formed from a first material, and
 - the plurality of concentric grooves is at least partially filled with the first material.
10. The system of claim 9, wherein:
 - the first material is silicon; and
 - the lens layer is formed of a metal material.
11. A portable thermal imaging system comprising:
 - a portable housing configured to be carried by a user;
 - a bolometer sensor assembly supported by the housing, and including a substrate having an upper surface supporting an array of thermal sensor elements and a cap wafer directly supported by the upper surface and including a cap layer spaced apart from the substrate, the cap layer supporting at least one plasmonic lens;
 - a memory including program instructions; and
 - a processor operably connected to the memory and to the sensor, and configured to execute the program instructions to
 - obtain signals from each of a selected set of thermal sensor elements of the array of thermal sensor elements,
 - assign each of the obtained signals with a respective color data associated with a temperature of a sensed object, and
 - render the color data.
12. The system of claim 11, wherein the at least one plasmonic lens comprises:
 - a plurality of grooves in a lens layer, and an opening extending completely through the lens layer.
13. The system of claim 12, wherein the plurality of grooves comprise:
 - a plurality of concentric grooves.
14. The system of claim 13, wherein the lens layer is supported on an upper surface of the cap layer.
15. The system of claim 14, wherein:
 - the cap wafer is formed from a first material, and
 - the plurality of concentric grooves is at least partially filled with the first material.
16. The system of claim 15, wherein the portable housing is a portable cellular telephone housing.

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